PSYCHOPHYSIOLOGICAL CHARACTERISTICS OF THE SOLUTION OF MOTOR PROBLEMS BY MAN

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The further development of space flight is dependent on the reliability of the human being as a biological system, that is, on the degree of his resistance to unfavorable flight factors as well as on the limits within which he can be trained to be stable to such factors. However, even successful solution of the problem of the reliability of the human being as a biological system does not furnish a complete answer to the problem.

The second aspect of this problem is intimately connected with determining the control and communication functions that can be entrusted to an astronaut. Obviously, it is expedient to have a man aboard a spacecraft when we think that he will be able to carry out those functions of controlling a spacecraft, the communication system and the flight situation as a whole that even the most highly perfected machine cannot do. /28

At the present time, psychology and physiology are hardly in a position to provide a clear answer to this question, since it has never risen before in this formulation and since it still requires much and varied research. Obviously, this research work will have to develop along two principal equal lines: 1) a theoretical study of the higher nervous activity of man within the scope of the problem "man as a link in a control system"; and 2) a study of the specific control functions, under optimally real conditions, using trainers, simulating some of the actual equipment of spacecraft control systems.

At first glance it may seem that the second line of research will yield a clean answer to the question as to whether and how man can handle the control systems simulated in the trainer. However, a closer examination reveals that such a method can never yield a fundamental solution to this problem or a prediction of human behavioral patterns under work conditions with certain new, untested control-panel designs or under conditions in which new problems arise.

At the present time, study of the higher nervous activity of man urgently requires analysis of his effector activity. As technology develops, the effector activity of man, being most completely representative of his professional acumen, is changing more and more distinctly from the category of motor skills to what may be called the solution of problems.

In this connection, the most important of the requirements imposed by such type of activity are those on the higher organs of control of activity itself, on the higher nervous activity of man. At the same time, the classical ideas of the higher nervous activity of man do not include an analysis of his effector activity; in essence, they reduce this activity to a sum of simple single actions (answers) to signals from without. Such ideas are insufficient, because in our opinion they

do not contain the principal characteristic of higher nervous activity, which involves organizing the process of doing something and which determines every kind of human activity, especially professional activity.

The aim of the present paper is to summarize the experimental work and the resultant hypotheses on the methods of organizing the effector activity of man. The experiments were carried out by a team from the I. P. Pavlov Institute of Physiology (N. A. Rokotova, I. D. Bogina, I. M. Gorbunova and Ye. S. Rogovenko) from 1962 to 1965.

Dynamic Human Stereotypes as Programs /29

Precision of action is ensured when the motor act is organized in such a way that the process is completed by the minimum groups of muscles necessary for the given problem and that the muscle contractions of these groups are time-correlated. Economy of motion is further narrowed down by saying that the effort exerted by each muscle and group of muscles can also be said to be the minimum necessary to solve the given problem [28]. However, organization of the motor act does not exhaust the problem of organizing action, since we are still left with the problem of correlating individual motor acts. In its most obvious form, this question arises when the complex of motor acts consists of several motions, each of which is familiar to the human being (i.e., the motor act itself is organized with respect to coordination).

This is true of motor acts in which machinists or pianists depress keys or an operator standing at a console presses buttons or turns handles. How does a man who skillfully performs a sequence of actions differ from an untrained man? One of the possible answers is that skillful performance is distinguished by the highest precision and by the rate at which individual motor acts are carried out in succession. In the opinion of various authors the reasons why motor sequences are carried out effectively can be found: a) in the motor system itself; b) outside the motor system; and c) within the framework of control of motor acts.

The first viewpoint, which was formulated by Campbell [7] as early as 1936, reduces to the existence, so to speak, of general motor or technical capabilities. A corallary of this viewpoint is that there should be some correlation between the level with which one motor skill is performed and another. However, the numerous studies made by Seashore [15] on the basis of a large amount of material have proved convincingly that this viewpoint is without foundation and that there is no correlation between different forms of motor skills. Seashore's results indicate that the performance of individual types of sequences of actions is of a very specific nature and lead us to believe that actions are organized at the level of some definite sequence or motor problem, governing the specific nature of the given motor skill.

The basic concept underlying the second viewpoint is that the level of the motor skill (performance) is determined by the logical side of the problem, i.e., by the flow of information received from without. This is the reason for the many investigations of the motor response time as a function of the physical and informational characteristics of a signal. A number of studies [5, 25, 26] /30

demonstrated that a response time of 100-150 msec to a single signal increases, e.g., to 800 msec when the signal carries eight alternatives (possible decisions), that is, three bits of information. On the basis of this viewpoint, let us consider the work of a trained typist typing some text from a sheet of paper. We know that a letter of the Russian alphabet carries 5 bits of information (there are 32 letters, i.e., it is possible to make one of 32 decisions in recognizing the letter on the keyboard before pressing the key). This quantity is distinctly greater than the one (3 bits) that requires no less than 800 m sec from the time the signal is produced to the time the key is pressed. Let us assume that this time does not increase beyond 800 m sec. This means that the rate at which the typist should work is somewhat more than one letter per second. This is a rate which corresponds approximately to the concept of "channel capacity" in communication theory; in magnitude this rate is similar to the experimentally determined transmission capacity of a human [30], which amounts to about 6 bits/sec. At the same time, we know that an experienced typist can type 4-6 symbols per second. Special studies of the amount of information at such speeds have shown that the quantity of information in this case would be about 25-30 bits [32, 33].

Such a serious discrepancy between the real performance index of an experienced typist and the theoretical level that might be achieved if the speed and accuracy of the work were governed only by the flow of input information indicates that these concepts are insufficient.

The third viewpoint combines the reasons for the effectiveness of motor skills and control of motor acts and develops ideas as to the hierarchy of programs that can be used to control the different variables that make up an organized sequence of motor acts. The program is a certain description of the performance process. It may resemble a sheet of paper with written instructions concerning the enumeration, order and method of performing individual operations making up the given motor problem. In other words, the program is a sum of the instructions as to how a problem is to be carried out (such instructions for the typing operation might be: find the necessary letter, identify, move the hand, put the finger in contact with the keyboard, lift the finger, check the result, etc.).

A hierarchy of programs is a concept relating to a stratified programming structure, which is reminiscent, e.g., of the structure of administrative control. The top command level gives only the most general instructions which, as they descend the hierarchical ladder, become progressively more fragmental and specific. It can be imagined that the lowest rung of the ladder of motor programs is a set of instructions to definite groups of muscles ordering them to contract, /31
so as to give finality to the required work posture, whereas one of the highest rungs is associated with instructions for prescribing the order of the actions involved in the task (using the typist as an example, take a piece of paper, insert it, transport the lines, type, etc.) and for prescribing the working mode (the speed which governs the length of the intervals between individual actions).

Ideas on behavior as a sort of program are not new in physiology, even though they have only recently been given the impetus for rapid development as a result of the success achieved in other branches of science. In his investigations I. P. Pavlov came quite close to a similar idea, as is indicated by such approaches in his work as the consideration of a dynamic stereotype, time reflex and reflex when a reference is made to a point of reinforcement in a series [9]. In 1963

Asratyan [2] pointed out the program nature of a stereotype. Furthermore, we should mention the ideas proposed in 1947 by N. A. Bernshteyn relating to the steps involved in motion [3]. The voluminous evidence cited by the author concerning the description of certain motor tasks is a convincing argument that actions are carried out according to a program.

In 1951 Lachley [27] formulated the idea that the principles of various forms of behavior (verbal, motor, professional) are general. He examined the order of actions in a sequence and stated that not only speaking, but also motor acts present us with the problem of time integration of the sequence, the problem of ordering individual activities in a certain time interval.

In the last four years the development of programming concepts as the basic principles for understanding behavioral mechanisms (especially motor problems) is characterized by the appearance of a number of works of theoretical nature in which various schemes for program control of behavior are suggested [4, 19, 24, 31]. The authors of these articles have brought forth many useful arguments, but the physiological value of the schemes they proposed is as yet unclear.

The development of programming concepts in describing the behavior of man has a number of advantages over other representations of human behavioral mechanisms. It has simplified, e.g., understanding of certain pathological forms of behavior such as apraxia, because they can be examined as a disease of the programming mechanisms. Simplified in the same way is the description of certain conditioned-reflex forms of behavior such as the time reflex or reflex to alternating reinforcement. In order to describe conditioned time reflex in the language of conditioned reflexes, it is necessary to draw on a number of additional explanations, since the conditioned time reflex does not contain a conditioned signal in the usual sense, and it cannot be realized only once. However, the features characterize the usual conditional reflexes. The idea of a program that /32
can be used to deliver individual responses over equal time intervals simplifies the understanding and description of conditioned time reflex.

Thus, the problem of programmed behavior mechanisms is very important to the science of higher human nervous activity, and in this connnection it must be noted that the amount of experimental investigations in this domain is unaccountably small.

In 1932 Lamley [8] demonstrated that man can be taught a series of actions formed only on the search principle. A man stood before a typewriter and was presented the problem of selecting a letter in the mind of the experimenter. Since the experimenter had a program with a fixed order of letter choice, the test subject could discover the expermenter's system of actions and could reduce the number of searches by formulating a system (stereotype) of responses. Subsequently many authors carried on their work using the search approach to study systematic behavior. This type of problem is an example of a certain stereotype developed without the aid of external signals.

I. P. Pavlov showed that the idea of a stereotype consists in the formation of a connection between individual conditioned reflexes by repeating their order of sequence. The classical proof of this fact is the experiment in which the external conditioning signals were discarded, leaving the order of succession of the responses unchanged.

In our experiments it was shown that the property of a stereotype to control the order in which responses are made is stable, making it possible not only to eliminate signals after the stereotype has been taught, but also to organize the process of teaching a stereotype independently of external signals. This property was studied by us both in higher animals and in man [11, 12, 13].

The existence of forms of behavior in which knowledge of the response to be made is based on interrelationships between responses distributed in a certain order raises the problem of control programs in which the position of each response in the sequence is fixed.

The fact is, as our experiments have shown, that man is capable of developing stereotypes of up to 48 components in length without external signals [14]. Since such stereotypes do not contain signals indicating which response can be found, say, in the 36th position of the stereotype, such indications must be provided by some sort of control mechanism. In order for such a mechanism to issue responses, while preserving a strict order, it must be either of the computer type or must be based on relations between individual responses. A mechanism which counts the number of components in a stereotype when the stereotype is of considerable length is uneconomical and cumbersome. A mechanism based on relations between responses is more favorable, because not all the responses in the stereotype need be enumerated, a relationship need only be established between several responses. Let us illustrate this with an example. /33

Let us imagine that we have presented a man with the task of developing a stereotype under the condition that there are two signals (denoted below as "red" and "green") which are to be used in making one of two responses, say, depress one of two buttons. The stereotype consists of 9 units; the order of sequence of the signals and responses is presented in Columns 2 and 3 of Table 1. the problem is: how will the man behave after developing the stereotype if we get rid of the signals and change them by repeating one signal, e.g., the red one? From the classical experiments we know that in the same situation animals repeat the number and order of the responses developed in the stereotype. But in this case man, more often than not, will begin to repeat response 1, which is related to actuation of the red signal. At the same time, if he is asked to repeat the learned order of response to the action of only the green signal, he will be able to reproduce this order. This means that the mechanisms governing the response activity of man under such conditions involves, in addition to fixation of the order of responses, the formulation of a rule of the type "the red signal requires the first response." In connection with this rule it has proved to be possible, e.g., to make any arbitrary increase in the number of signals and to make any combination of them. Thus, the sequence of response actions ceases to be dependent on the number of signals used, but is based on a rule connecting a specific signal with a special response.

This is one aspect of the response activity. Another aspect is connected with the fact that a human being repeats the order of events, when the order of the signals is changed, by repeating one signal. In the case of the stereotype described in the left half of Table 1, in order to reproduce the order of events it is necessary either to memorize the entire list and order of the signals and use the rule whereby the signal is related to the response or to memorize the entire /34

TABLE 1. Problem of Developing a Stereotype With Two Signals

Successive numbers of the stereotype units	Original order of the signals	Order of the responses	Change of the original combination	Order of the responses
1	2	3	4	5
1	Red	1	Red	1
2	»	1	»	1
3	Green	2	Green	2
4	Red	1	»	1
5	Green	2	»	2
6	»	2	Red	2
7	»	2	»	2
8	Red	1	Green	1
9	»	1	Red	1

list and order of the responses. In either case, the delivery of a response in the stereotype order evidently requires enumeration of all the components of the stereotype.

Hence, analysis of such stereotype still does not yield an answer to questions concerning the mechanisms which indicate position in a stereotype on the basis of knowledge of the relationships between neighboring acts. Now let us turn to the right half of Table 1. Here we are also dealing with a stereotype as well as with a definite order of the responses. Here, however, the relations between the individual responses are governed by other characteristics.

The fact is that this characteristic is based on rules governing the relations between three events: two neighboring actions—the past and present—and the present signal. Man can formulate these rules for himself approximately as: "on the red signal stay where you were the last time; on the green signal, change position." In this kind of stereotype the order of signal succession can be completely random, whereas the response behavior is completely systematic. The system of responses in this case is connected with the acting signal as a condition defining which signal is to be used in giving the next response. Such relations between external signals and responses are similar to the input and system relations in technology, and therefore we have denoted Column 4 of Table 1 as a "replacement of the input signal combination." This kind of stereotype was developed in more than 30 men [14].

It is clear that the possibility of experimental development of such behavioral systems in man leads us necessarily to ideas of control programs and to clarification of the problem of the component parts of control programs.

The Teaching Process as Synthesis of the Order-of-Action Program

In 1948 Woodworth formulated the motions of two-phase and polyphase motor units [34].

Expanding his notions, Fitts discovered the nature of the polyphase unit and stated that it may be precisely this unit which is a component part of the performance program [24].

The concept of a two-phase motor unit is a concept relating to a single motor act such as grasping, pressing, throwing, jumping, and consists of a preparatory phase (to squeeze it is first necessary to open one's fingers) and an effector phase (the grasping act proper). In its simplest form a polyphase unit is a sequence of several two-phase units, that is, a larger or longer piece of motor activity which, obviously, is somehow connected (e.g., connected with the fact that individual acts are successive in time and are done repeatedly in the same sequence). /35

In our experiments we found that individual acts are grouped together in a motor sequence. Subsequently we made a special study of this fact, so that now we possess data which enable us to single out the individual forms which the phenomenon of action-clustering takes on [12, 13]. Let us consider some examples.

Magnitude of the Gain in Number of Actions During the Learning Process. Imagine that it is necessary to memorize a certain sequence of motor acts, and that this sequence is so long that it cannot be memorized at one time. Let us say that the sequence consists of 36 individual actions. Let us consider a teaching method in which the entire chain of events that must be learned is somehow presented, and each time it is presented we will ask that what was memorized be repeated.

The general course pursued in solving such problems reduces obviously to the fact that the number of the repeated actions increases from presentation to presentation until all 36 actions are reproduced. The question arises as to how many actions are added to the part already learned in one showing or for each repetition. In our laboratory we carried out experiments aimed at solving this problem. In brief, the essence of the experiment reduces to the following. We made up two problems of learning and repeating a sequence of actions. Each action consisted of pressing one of eight keys of a special panel. The keys were arranged in two rows of four each and occupied an area of 8 x 20 cm.

Both problems contained 36 actions to be accomplished in different order. In setting up the sequential list of actions we took into account the location of the keys over the surface of the panel. From our previous experience we knew that people lump together individual key-pressing actions on the panel when these actions are carried out on keys in a row or when the transfer of the hand from one key to the next described some geometrical figure. This fact served as a basis for putting together the problem in this series of experiments. The 36 actions of which problem 1 was composed were arranged in such an order that every four actions (first to the fourth, fifth to eighth, etc.) could be lumped together. In problem 2 the 36 actions were arranged in such an order that every 3 or 6 actions could be grouped together.

The learning procedure consisted of instructions in which the problem was to learn and repeat the order of the 36 pressing actions, of the learning process itself and of the subsequent multiple repetition of the stereotype by heart. The /36 procedure was carried out by repeatedly demonstrating to the test subjects the

entire sequence of actions, followed by a repetition of what had been acquired (immediately after terminating the demonstration). A set of eight light signals arranged in the same way as on the panel served for the demonstration. The test subjects were acquainted with the unique relationship between the signal and the key and were then shown the order of the actions by consecutively flashing the respective signals.

A twelve-man group of test subjects was selected to learn both stereotypes. One half of the group was taught problem 1, and three days later problem 2; the second half fulfilled this task in reverse order.

In order to solve the problem of the magnitude of the gain we counted all differences in the number of repeated elements between successive repetitions in the learning process. For example, if the test subject repeated 6 actions after the first presentation of signals, 10 after the second and 13 after the third, the respective differences making up the magnitude of the gain was 6, 4, and 3 actions.

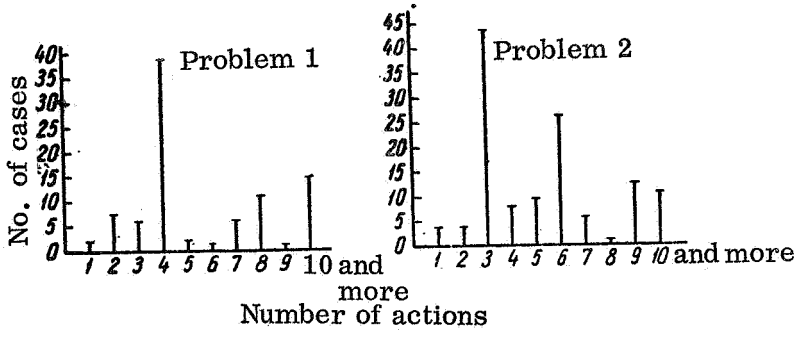

Figure 1. Distribution of the Number of Actions Gained in Each "Step" of the Learning Process as a Function of the Structure of the Problem.

Shown in Fig. 1 are summary data covering the entire group of test subjects, characterizing the size of the gain from repetition to repetition. From the figure it is evident that cases of only a single-action gain are the rarest. Most frequent are the magnitudes of those gains which correspond to the structural features of the problem (4 actions for problem 1 and 3 and 6 actions for problem 2). Consequently, the learning process is of a nonuniform, discontinuous nature, the nonuniformity evidently being connected with the formulation of a control program consisting of certain blocks containing several clustered motor acts.

A more detailed description of this series of experiments is given in an article written in conjunction with I. M. Gorbunova: "On certain features of programming a sequence of human actions," which can be found in this collection. /37

Transposing Blocks of Actions in Learning a Stereotype. The discontinuous nature of the process of learning a stereotype is associated with the blocking process, that is, coupling individual responses into certain blocks. There is

reason to believe that these blocks have the character of a new, closed behavioral unit (not unlike the polyphase motor unit of Woodworth and Fitts). In experiments on a 30-man group of test subjects who learned a sequence of 36 actions (problem 1 given above) we analyzed the responses of the test subjects from the viewpoint of coincidence between a sequence of responses and consecutive positions in the stereotype. The results of this analysis are given in Table 2 in the form of a distribution of errors committed by the group of test subjects during the same learning periods. Selection of the errors committed by the test subjects was based on the fact that a correct response was considered to be only a response made at the point that corresponded to its correct position in the stereotype. Hence, the responses which reproduced individual elements of the stereotype, but were not made at the correct points, were considered as errors. In such a context it was found that the bulk of the errors stemmed from clustered actions arranged in an order that differed from that in the given stereotype. As is evident from Table 2, after 20 learning repetitions, 55% of all errors were due to the fact that clusters of responses corresponding entirely to specific parts of the problem were not reproduced at the correct points; the remaining errors were also connected with the effect of grouping actions. Only 20% of the errors were not connected with coupling of actions into blocks.

TABLE 2. Error Distribution in Repeating a Sequence of 36 Actions

Learning level	Overall number of errors	Error distribution (%)					
		Total errors	Transposition of correct blocks	Transposition of distorted blocks	Total no. of group transposition-errors	Simple grouped errors	Random errors
After 10 repetitions	510	100	38	23	61	37	2
After 20 repetitions	385	100	55	21	76	22	2

Remark: 30 test subjects participated in the experiments.

Thus, the integrity of a block of actions is supported by the fact that the block was freely transposed, while preserving the order in which the coupled motor acts were arranged. /38

Selection of Coupled Blocks of Actions. The nonuniform, or discontinuous nature of the learning process is connected with the process of clustering actions and comes to light in another way. If the stereotype is learned from the very start without any relationship with specific signals, but by searching for or guessing each individual consecutive action, it turns out that the order in which individual actions are acquired does not correspond to their consecutive positions in the stereotype.

Twenty test subjects worked through a stereotype consisting of 20 actions, each of which had to be found from among 8 possible motor acts (in somewhat the same way as with Lamley's printer). During this test not once did we observe the process of accumulation of a sequence of correct responses, which would

have meant a gradual increase in the number of terms as well as maintaining them in order (first the 1st term of the stereotype, then the 2nd, 3rd ... 20th). A typical case of learning such a stereotype is shown in Fig. 2, which presents the experimental record of test subject V-ts. The black squares, which show the positions of the correct responses, clearly demonstrate the presence of the process of coupling individual correct actions and of singling out a coupled group of responses to which more and more new responses are added to each side. /39

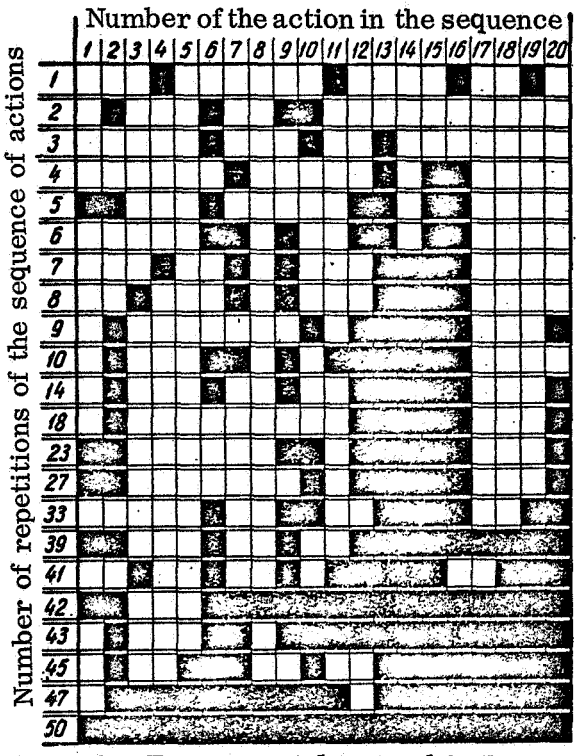

Figure 2. Experimental Record in Learning a Stereotype by the Search Method. (Test subject V-ts.) The Open Squares are Errors, the Solid Ones Correct Responses.

Thus, there exists a number of proofs of the fact that learning of a stereotype is connected with the process of forming, singling out and combining groups of motor acts.

Coupled blocks of response actions are built up in such a way that it is possible to give a general description of a block. This indicates that the human control nervous system has a program-type of control mechanism in which concrete programs are set up (synthesized) in learning a new motor problem. Evidently, under the conditions of the problems described above, the programs are composite, consisting of several elements or subprograms, such as the structures that ensure the execution of a coupled group of actions.

CENTRAL MECHANISMS GOVERNING THE TIME DISTRIBUTION OF MOTOR ACTS

Rhythmic Pattern of the Time Distribution of the Process of Executing a Stereotype of Actions

In order to formulate a hypothesis on the location of the grouping process in mechanisms of the control program, it is necessary to draw on ideas relating to the hierarchical structure of programs, which was discussed at the beginning of the article. In connection with the above-described results of analysis of the stereotype learning process, it might be assumed that the process of forming a block is independent of the process of joining blocks. Then, based on published viewpoints on the hierarchy of programming mechanisms, it is permissible to assume that block-forming processes reflect two levels of mechanisms in the control program.

The upper level issues instructions on the order in which blocks of responses are made, whereas the lower level controls the order in which the individual responses making up the blocks are delivered. If this hypothesis is correct, it can be expected that the total time for performing a stereotype will not be uniformly distributed. In particular, it can be expected that the interval separating adjacent actions of different blocks will be different from the interval that separates adjacent actions of one block.

In connection with these ideas we made repeated measurements of the time /40
for performance of a stereotype after learning the above-described problems of a sequence of 36 key-pressing operations. Measurements were made of all the time intervals for peforming the sequence of actions.

A tenfold record of the performance of the stereotype was made on a multichannel loop oscillograph and measurements were made by examining the tapes on a photoampilifier provided with a measurement grid. We measured the time spent by man in executing the individual actions of the stereotype and the length of the pauses between adjacent actions. For each test subject we computed the average values of ten measurements and then computed the arithmetic means of the group of test subjects and the rms deviations.

Presented in Fig. 3 are data on the length of the pauses between individual motor acts as a function of the location of the pause in the stereotype. Given in the upper half of the figure are the values which characterize the execution of problem 1 and in the lower half, of problem 2. Verticals were drawn from the peaks of each curve. From the figure it is evident that the distribution of time intervals is specific for the execution of each problem. Thus, the peaks of the curve characterizing the execution of problem 1 refer to the 8th, 12th, 16th and 20th positions, while those of the curve describing problem 2 relate to the 6th, 9th, 12th, 15th and 18th positions of the stereotype. The values of the rms deviations, which characterize the degree of individual scatter, do not overlap the characteristic rhythmic pattern of each stereotype.

Thus, the rhythm of the time pattern of a stereotype is described by the greater magnitude of some pauses as compared with adjacent pauses. The longer pauses are found at the points where the individual blocks making up the stereotype join. The fact that the problem is specific shows up in the number and size of the groups and is detected in the distribution of the completion-time intervals. Consequently, clustering is that sign of an ordered sequence of actions that characterizes not only the learning process but also the execution process.

It must be noted that a number of authors have drawn attention to clustering phenomena in other forms of motor problems, such as alternating motion of the right and left arms [10], load-lifting motion [16], walking in a maze [23], as well as in other forms of response activity (repetition of a sequence of letters by naming them [20]).

Stability of the Rhythmic Pattern of a Stereotype. The idea that the distribution of the time intervals in a stereotype creates the specific rhythmic pattern of the problem can be strengthened and verified by investigations devoted to the stability of the rhythm to a change in the overall working speed as well as to the /41
degree of training of the test subject for the given task.

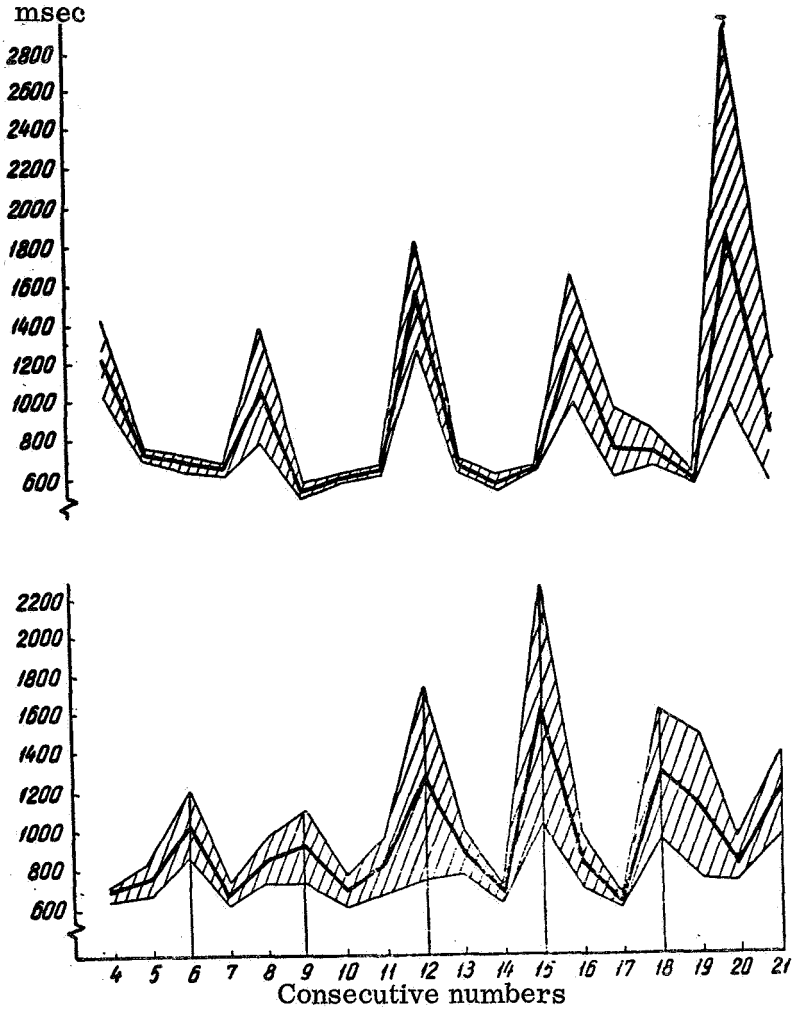

Figure 3. Time Distribution (pauses between adjacent actions) in Carrying Out a Stereotype as a Function of the Structure of the Problem.

Formulation of the problem of the effect of speed on the rhythmic structure of a sequence is due to L. A. Chistovich [18], who demonstrated that the rhythmic structure of the spoken language does not change with the speed. In our research we found similar facts applying to the execution of motor tasks. The experiments were conducted in the following fashion: After learning a sequence of 24 actions, 15 test subjects were required to carry out the sequence several times at their best speed. At the same time the experimenter noted the time it took to perform the task. Then he asked the test subject to work at precisely that tempo as smoothly as possible and to keep within a time interval limited by start and finish signals. The aim was to make the last action of the test subject coincide with the finish signal. Ten executions of the stereotype were recorded on the oscillograph at this original tempo. In addition, the test person was asked to reduce the tempo by one and a half. Now the finish signal was given after a

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start-finish time interval greater by a factor of one and a half than the original one. Ten executions of the stereotype were recorded at this tempo. Finally, the test subject was asked to return to the original tempo and again ten executions of the stereotype were recorded. Each time the tempo was changed the experimenter changed the time interval limited by the two signals so as to correspond. The results of measuring the individual time intervals for executing the stereotype revealed that the rhythmic pattern of the problem was preserved when the work tempo was changed. These data are shown in Fig. 4. Each point represents the arithmetic mean of ten measurements of the period required to perform an individual act (the time it took to move the hand plus the pressing time) expressed in fractions of the total period during which the task was fulfilled. It is clearly evident that the rhythmic pattern of the stereotype is invariant, indicating that the temperal distribution of actions in a stereotype is stable with respect to the overall performance speed (tempo).

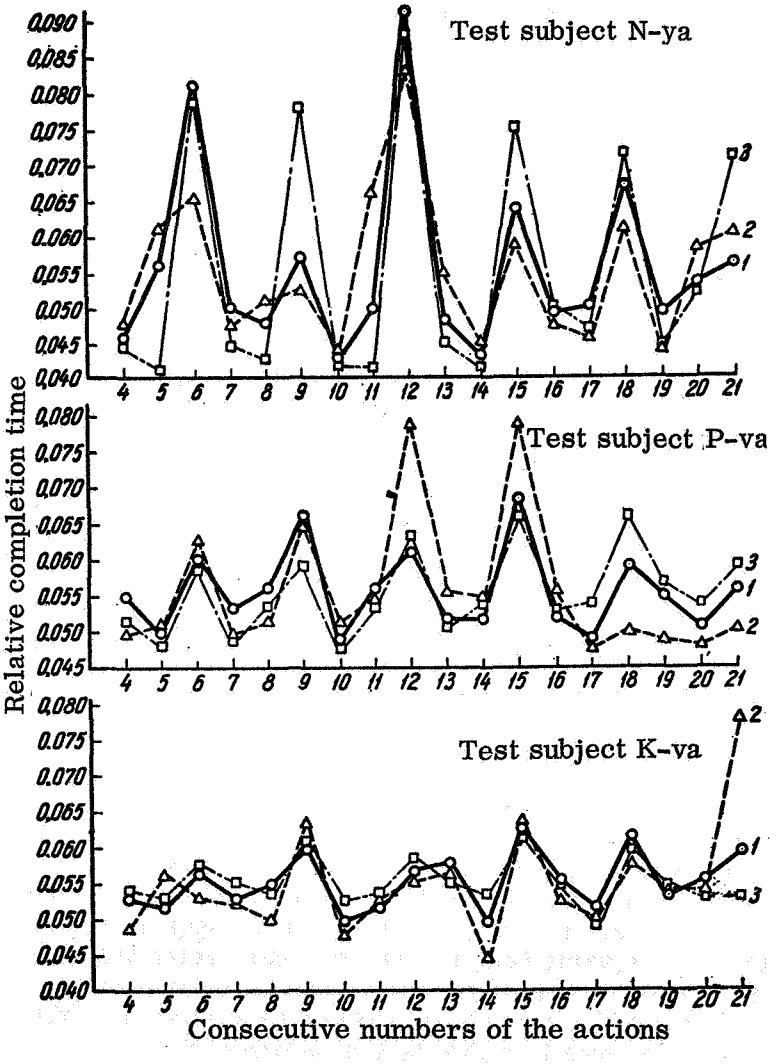

Figure 4. Distribution of Time During the Execution of a Stereotype at the Optimum Tempo (1), at a Tempo Slower by a Factor of 1.5 (2) and at a Tempo Accelerated by a Factor of 2 (3).

In others of our experiments it was found that the rhythm is stable to repeated execution of the task. Six test subjects were trained in a hundred repetitions to execute the same sequence of actions. The "automatic" nature of the performance was tested by asking the test subject to count the light flashes aloud while executing the task. It was found that the rhythmic pattern of a stereotype remains invariable.

Thus, the specificity of the control program consists in the existence of such characteristics in the learning and performance process as the association of motor acts in groups as well as in the stability of these characteristics to certain perturbing effects.

The Process Underlying the Uniformity with which a Stereotype of Actions is Performed

In studying the process of performance of a sequence of actions by a human being we directed our attention to the uniformity of the work of the test subjects. Repeating the same series of experiments over and over again with an unspecified time schedule, man sets his own schedule, so to speak. This is evident from the fact that the total time it took to carry out the series of motions became stabilized. In experiments carried /44
out by Miss Savilova, a student, the test subjects repeated a learned sequence of key-pressing actions on the experimental panel tens of times. The sequence consisted of 36 motor acts executed always in the same order. Each pressing act was recorded on a multichannel recorder with a moving-picture film. Counts of the time it took to execute the sequence revealed that each test subject repeats it within a certain fixed time interval. Thus, test subject K-va performed the series of motions in 18.910 ± 0.130 sec (76 measurements), while test subject T-va executed the same series of motions in 26.150 ± 0.310 sec (45 measurements). The mean error in the first case was 0.6% of the arithmetic mean, and in the second case 1.2%. Such high accuracy in repeating one and the same time interval cannot be accidental. At the same time, the work tempo was not prescribed in any way; the test subjects freely repeated the series of learned motions from memory at an arbitrary tempo. Hence it was postulated that the human nervous system contains a mechanism which controls time intervals.

There can be no doubt but that the central nervous system of man possesses the property of measuring time intervals. The widely known work of Pavlov's school on conditioned reflexes to time clearly illustrates this property [9]. In recent years, the investigations of M.A. Alekseyev et al. [1] have shown that man estimates time intervals with a high degree of accuracy. In all these cases we have been speaking about the measurement of time intervals limited by signals external to the human being, that is, of imposed rhythms, not of natural ones. But whenever man works at a certain tempo fixed by himself and not limited by external signals, it is necessary to be capable not only of measuring time intervals, but also of generating them. It is natural to assume that the nerve system has this property also. Rhythmic contractions of the heart, walking, running, swimming and many other forms of activity are obviously sequences with a specified rhythm or (what is the same) with fixed intervals. The well-studied fact of the diurnal rhythm inherent in living organisms is understood by many researchers as the generation of internal, so-called circadian rhythms [6].

A model of a mechanism generating time intervals of the length in which we are interested was studied by McGill [29]. The basic mechanism generates regular excitations which, however, cannot be observed. Accessible to the observer are the responses, each of which arises as the result of successive excitation, with a certain random delay. Hence, the observed intervals between responses contain a random component (delay) and a regular component (fixed interval). Shown in Fig. 5 (from McGill) is a diagram of such a mechanism, where τ is the time interval (fixed) between two excitations, S is the delay between successive excitations and the instant the response is made (random), r is the time interval between the successive response and the next excitation, and t is the observed interval between responses. /45

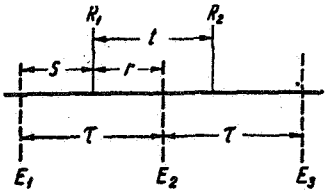

Figure 5. (From McGill). E_1, E_2, E_3 are regular excitations: τ—is a fixed time interval between excitations; S—is the random delay between excitation and response; r—is the interval between a response and the next excitation; R_1, R_2 — are responses; t — is the observed interval between responses.

McGill shows that the distribution of S is not completely random, but that it is limited by the presence of a fixed interval τ, and therefore the values of S are distributed not in the interval $0 \leqslant S \leqslant \infty$, but in the interval $0 \leqslant S \leqslant \tau$. Hence, the distribution of the observed interval t differs from the normal distribution of the random function; in simplified form, it can be represented as the distribution of the Laplace function describing the operation of a periodic mechanism under "noise" conditions created by the random delay.

We believe that McGill's model may be a useful working hypothesis in analyzing the time it takes to complete a sequence of actions. An attempt to apply the model to a series of monotonic motor acts (pressing of keys) may help to explain the question of what is a unit (a fixed time interval τ) in a sequence of actions.

Under our experimental conditions, which were described in detail in [13], three levels of fixed intervals may exist: A-an interval during which the whole learned series of motions is carried out; B-an interval during which a group of actions less than the whole series, but containing more than one action, is performed; and C, c-intervals separating one action from the next. Hence, the problem of the present research reduced to measuring the intervals A, B, C, and c while repeatedly executing the learned sequence of actions (pressing keys on a panel) and to analyzing the distribution of these intervals. At the same time we expected to obtain one of two possible results: 1) if the given interval proves to be unspecified, its distribution may be close to normal; and 2) if the interval is fixed, its distribution differs from the normal and, according to McGill's model, approaches the distribution of the Laplace function.

Method /46

The experimental setup consisted of two large panels (25 x 30 cm). The test subject's panel contained 8 signal lights arranged in two rows of 4 each,

and 8 keys arranged in the same order. The experimeter's panel had 8 buttons to control the signal lights and 8 monitor lights for observation of the test subject's actions. The test subject was asked to learn and repeat a series of key-pressing actions on the panel several times, the series consisting of 36 or 24 successive pressing actions to be accomplished in a definite order. The pressing order was specified by the experimenter and was set up in such a way that the entire sequence could be divided into blocks of successive actions. In carrying out the actions making up a block the hand traverses a path forming, so to speak, a definite geometrical pattern or figure on the panel (e.g., a square, zig-zag, triangle, etc.).

The test subjects were persons of both sexes, in the 18-45 age range, with high-school or college education, and were volunteers.

The experimental procedure. As a preliminary, the test subjects were trained to execute a series of key-pressing operations on the panel in a certain order. After learning the series, they were instructed to reproduce the learned order of actions from memory. In different experimental versions, the test subjects reproduced a series of pressing actions from 10 to 100 times. The completion time was not specified in the majority of the experiments; in one series the time of completion of the sequence was prescribed, being controlled by the light signals: the experimenter noted the time of completion of the task, established a mean for each test subject, and then informed each test subject that it would be necessary to work each time within the same time interval. To do this, light signals were introduced, one giving the order to start pressing keys, the other (terminal) to coincide with the start of the last operations. The length of each specific interval corresponded with the average time it took the respective test subject to complete the task.

Recordings of the actions of the test subjects were made on the tape of a multichannel loop oscillograph. The tape speed was 4 mm/sec. The key-pressing motion was recorded on the tape in the form of a rectangular pulse. The pulse length corresponded to the key-pressing time. The separations between intervals corresponded to pauses between two pressing actions (the time it took to move the hand from one key to the next).

The parameters were measured on the tape by means of a photoamplifier, with a measuring grid, having an accuracy of up to 50 m sec. Let the time of completion of the entire sequence be denoted by A (Fig. 6). It is the sum of all the intervals ($l_1, l_2, \ldots, l_n$) during which the keys were pressed and of the intervals ($c_1, c_2, \ldots, c_m$; $C_1, C_2, \ldots, C_k$) between pressings. The "c" intervals separate actions within a cluster, the "C" intervals separate clusters of actions. The segments $B_1, B_2, \ldots, B_{k+1}$ represent the time expended in executing a block of actions.

Analysis of the Measurements. Over all the above-listed intervals we calculated the average values and the rms deviations, estimated the distribution, and computed the relative errors (σ/x) and relative errors of the mean (m/M).

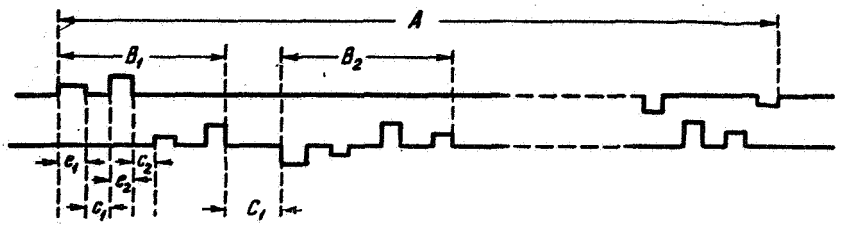

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Figure 6. Schematic Representation of a Record of the Time Required to Execute a Sequence of Actions:

A—Time to Execute the Entire Sequence; B_1, B_2—Time to Execute a Block of Actions; C_1—Pause Between Blocks; $t_1 - t_2$—Length of Key Pressing; c_1, c_2—Pause Between Successive Pressings (the hard transfer-time)-Pause Within Blocks.

Time of Execution of the Entire Sequence of Actions (Distribution of the A Interval)

In analyzing the time required to complete the series of key-pressing operation in the given order, we attempted to solve the problem as to whether this time is a random variable. To do so, it is necessary first of all to obtain information on the accuracy with which man estimates the time to complete a problem when the time is specified by the experimenter. If we have such information, we can compare the magnitude of the deviation from the prescribed time with the magnitude of the deviations from the average values when the time of completion is not specified.

In the series of experiments carried out by student Kopylova, the group of test subjects was presented the task of learning a sequence of key-pressing actions and of reproducing the sequence from memory. The completion time was prescribed by the experimenter as described above (by means of light signals). With such an experimental setup, the time required to execute the entire series of motions in McGill's light model can be considered as a certain given interval whose fluctuations are a random component (noise) superposed on the regular process. The fixed interval τ (after McGill) is specified either by the experimenter (in this case its values are determined by the distance between the start and stop signals) or is set by the test subject (when its values are determined by the mean completion time). According to McGill, the random component measuring the "noise" relative to the magnitude of the entire cycle is equal to $1/\lambda\tau$, where $\lambda = 1/\sigma$. Thus, the quantity $1/\lambda\tau$ may serve as a criterion for the random component of a certain time interval.

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The eight test subjects performing the task were measured for deviations from the interval as fixed by the experimenter. To do so, the tape of the oscillograph which recorded the experimenter's signals and the test subject's actions measured the length between signals from the experimenter and the distance between the work-start signal and the last (24th) key-pressing action. The difference between these values was also calculated. No account was taken of the sign (+ or -) of the deviation. Then $1/\lambda\tau$ was computed for each test subject as

well as the mean $1/\lambda\tau$ for the entire group of test subjects (a total of 168 measurements). In this case the mean $1/\lambda\tau$ was 0.041, which represents the deviations from the fixed interval, if the interval is taken as being the one fixed by the experimenter. It is possible to estimate deviations from a fixed value under the assumption that the interval is set by the test subject himself. In this case the quantity τ will be the mean value of the interval, while $1/\lambda\tau$ will be a measure of the random component relative to the mean value. Calculations made in this way showed that $1/\lambda\tau$ of the individual test subjects has the same values (sometimes a little lower) as for the interval specified by the experimenter.

Given in Table 3 are data for three test subjects. From the data it is evident that the values of τ as measured by the experimenter's signals and by the test subject himself may coincide (test subject G-va), and then the values of $1/\lambda\tau$ also coincide, but when they do not coincide, the $1/\lambda\tau$ are lower for the interval measured by the test subject himself than for that prescribed by the experimenter.

TABLE 3. Fluctuations in the Time it Takes to Complete A Sequence of Actions Relative to An Interval Specified by the Experimenter and Relative to A Characteristic Mean

Test subjects	No. of measurements	τexperi. (m sec)	$\frac{1}{\lambda\tau}$	τcharac. (m sec)	$\frac{1}{\lambda\tau}$
B-va	25	16.750	0.043	17,050	0.035
G-va	25	17.900	0.014	17,900	0.014
S-va	23	19.735	0.037	17,650	0.035

In another series of experiments carried out by student Savilova, the test subjects repeatedly reproduced a learned sequence of 36 key-pressing operations; the time of completion was not prescribed. It was found that in such cases the test subjects themselves limit the time of completion, that is, they set the interval τ. /49

Given in Table 4 are data obtained from three test subjects. From the table it is evident that the values of $1/\lambda\tau$ do not exceed those obtained when the time was fixed. Hence it follows that when a human repeatedly reproduces a series of motions, he not only estimates the time of completion with high accuracy, but also marks off this time by a certain, only slightly fluctuating interval.

But these data still do not furnish an answer to the following question: is the time of completion of the entire series of motions a single fixed (prescribed) interval or is the uniformity of the time of completion of a series of motions governed by the presence of rhythmic processes of higher frequency? Isn't this interval the sum of smaller intervals which are also fixed, since we are dealing with discrete motor acts which are similar to each other? This question can be answered by analyzing the distribution of the values of the interval being

TABLE 4. Fluctuations of the Time it Takes to Execute a Sequence of Actions When the Time is Not Fixed

Test subjects	No. of measurements	τ, (msec)	$\frac{1}{\lambda\tau}$
I-va	30	17,000	0.039
B-va.	22	19,450	0.025
K-va.	40	18,800	0.021

considered. Such an analysis of the data we obtained in the different experimental series showed that the distribution of these values does not correspond to the distribution which is representative of McGill's model, which is characterized by the presence of a sharp peak and by a steeper curve. In our case we observed either a sloping asymmetrical distribution, truncated on the left (Fig. 7), or a distribution close to the normal, but truncated on both sides. It is possible that such a pattern is due to sampling which is insufficient for an estimation of the distribution (remember that the maximum number of repetitions of the series of motions did not exceed 100). Later on we intend to repeat these measurements with more statistics. However, the data we obtained are sufficient to determine that the given interval (the time of completion of the entire series of actions) does not correspond to the sharp-peaked distribution typical of McGill's model, and therefore cannot be evaluated as a unit interval fixed by a single pulse (or bounded by two control pulses). /50

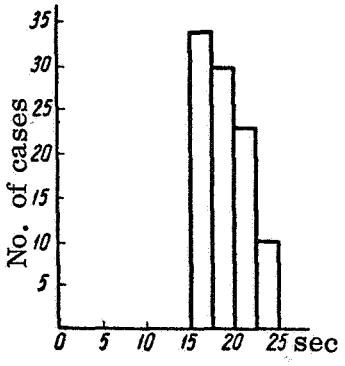

Figure 7. Distribution of the A Interval.

Time of Execution of a Block of Actions (Distribution of the Interval B)

The tasks our test subjects performed were sequences of simple monotonic motions organized in such a way that it was possible to combine several motions into a single complex. In the preceding work we examined these complexes and arrived at the conclusion that they represent a lumping process, and the segment of the sequence containing such a block can be considered as a new complex action consisting of key-pressing and key-to-key hand-transfer operations.

It was assumed that at the higher level of programming the order of the actions, a block of actions is specified as a whole, and is only then turned into a sequence of commands for execution of the individual actions making up the block. In connection with this hypothesis it was only natural to believe that the block of actions is time-ordered. And since the entire sequence consists of blocks and intermediate pauses, and the pauses are not fixed, it follows that the time segments during which these blocks are executed should be uniform and should fluctuate only slightly as compared with the pauses separating the blocks. These arguments were first drawn upon to analyze the construction of final control programs as applied to the speech function [18].

The time organization of the blocks was analyzed on the basis of data obtained from experiments with 9 test subjects. The test subjects learned, and repeated ten times from memory, a sequence of 36 motions made up of 9 blocks of 4 actions each. The time of completion was not prescribed. Since the blocks consisted of an identical number of actions, it was possible to compare data on the time in which the various blocks were completed. It was found that the time of completion of a block of actions by each test subject fluctuates insignificantly within one run of the series of motions as well as from run to run. It was found also that this time is similar for the different test subjects. On the whole, the group of test subjects was subdivided into two subgroups. The members of /51
the first subgroup completed the block of actions in 4,400 ± 31 msec ("slow"), while those of the second subgroup did it in 3,030 ± 34 msec ("fast"). The value of $1/\lambda\tau$ (0.106 for the first and 0.170 for the second) indicate that the random component plays some small role in forming these intervals. Histograms of the distribution of these intervals are given in Fig. 8. From the figure it is evident that the lengths of the intervals are different for each block, while each subgroup executes a section of the sequence within a slightly fluctuating time interval. However, an estimate of the distribution of the values we obtained did not reveal that it was similar to the distribution of McGill's interval, and therefore we have no reason to evaluate the time expanded in completing a block of actions as the interval limited by two control pulses. On the other hand, our data have shown that this time interval is less random than the interval separating blocks of actions, which confirms the above-mentioned hypothesis on such a structure for the process of ordering actions when the instructions are to execute the entire block of actions. From this hypothesis it follows that the time of execution of a block of actions should fluctuate less than the pause between blocks. Figure 9 shows these relationships.

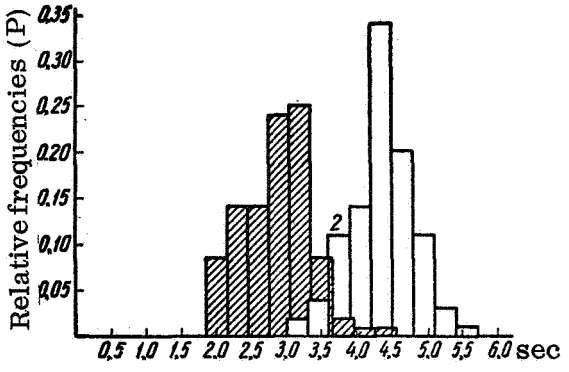

Figure 8. Distribution of the B Interval in the "Fast" (1) and "Slow" (2) Groups of Test Subjects.

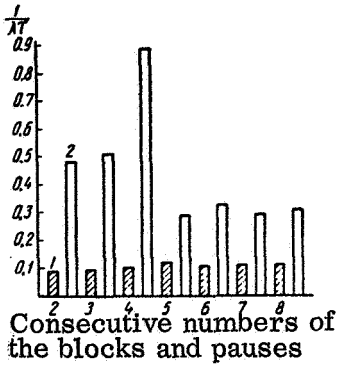

Figure 9. Fluctuations of the Time of Completion of Blocks of Actions (1) in Intergroup Pauses (2) of the "Slow" Test Subjects.

Given in the figure are the values of the random component ($1/\lambda\tau$), characterizing the time of execution of individual blocks of a sequence, and the length of the pauses separating these blocks. From the figure it is evident that the magnitude of the $1/\lambda\tau$ of the pauses is greater by a factor of 3 to 4 than that of the $1/\lambda\tau$ of the time for completion of individual blocks of the sequence. Consequently, the intervals

separating blocks fluctuate strongly. But if each of the separating pauses have a greater random component, and there are 8 such pauses in the entire sequence, /52
the overall error should increase, and the fluctuations of the total time of completion should reflect the sum of the fluctuations of the inter-block pauses, even if fluctuations in completing blocks are neglected. However, as mentioned above, the total time of completion of a sequence is uniform. This may mean that the inter-block pauses are not completely random intervals, but are related in inverse correlation, when strongly reduced pauses after individual blocks are compensated by reduced pauses after other blocks of the sequence. In order to track down this phenomenon, we intercompared the values of the individual pauses between blocks with their total value in the entire sequence. These data are presented in Table 5.

TABLE 5. Fluctuations of Intervals and Their Sum in the Group of "Slow" Test Subjects

Statistical index	Intervals between blocks							
	2–3	3–4	4–5	5–6	6–7	7–8	8–9	Sum
Arithmetic mean (M), msec	836	1253	992	824	724	851	730	6320
$\frac{1}{\lambda}$, msec	400	636	885	237	229	251	223	1690
$\frac{1}{\lambda\tau}$	0.48	0.51	0.894	0.288	0.315	0.295	0.305	0.27
m, msec	67	106	147	39	38	48	42	280

From these data it is evident that the mean lengths of the pauses between blocks differ from each other and are considerably scattered. But the fluctuation of their sum is somewhat less than might be expected. The magnitude of $1/\lambda\tau$, which characterizes the sum of the inter-block intervals, is less than the $1/\lambda\tau$ of any of these intervals, and the magnitude of $1/\lambda$ of the entire sum is less than the sum of $1/\lambda$ for individual intervals, which could not be true if the random intervals were added together. Thus, there is reason to believe that the inter-block pause, just as the block of actions, is time organized. Before making a decision as to the structure of this organization, let us consider what characterizes the time of completion of a single action in the sequence.

Time of Completion of a Single Action and the Distribution of the Intervals "C," "c" /53

The time of a single action was measured for various versions of the experiment with the time of completion of the sequence specified and unspecified.

A single action in our experiments can be considered either as the motions of key-pressing or of transfer of the hand to the next key, separately, or the pressing and transfer acts can be considered jointly as a single action, that is, the complete cycle of motions necessary to carry out one action in executing

consecutive key-pressing operations in a definite order. In order to decide which of the time intervals in this case can be considered as specified, the measurement results were analyzed both separately with respect to the pressing time and hand-transfer time, and jointly as the pressing time plus the transfer time. The hand-transfer time, i.e., the pause between two pressing operations, is considered here as applying only to the execution of actions within blocks. The pauses between two pressing operations referring to different blocks (inter-block pauses) were not included in these measurements and are considered separately.

The results we obtained can be reduced to the following principles: 1) the time interval which represents the sum of the pressing and hand-transfer time exhibits less fluctuation than the time segments of which the interval is composed; 2) the distribution of each of the intervals we considered differs from the normal and approaches the distribution of the Laplace function; 3) the magnitude of the random component for each of these intervals does not depend on whether the time of completion of the entire series of motions was prescribed by the experimenter. These principles were illustrated in Figs. 10, A, B, C.

Presented in Fig. 10, A, are the distribution curves for deviations from the arithmetic mean for pressing-time intervals, hand-transfer time intervals, and for total time of the motion (the pressing + transfer times). The curve was constructed from data of a group of test subjects who completed a sequence of 24 key-pressing operations on the panel under specified time conditions (980 cases). From the figure it can be seen that the minimum values of the deviations (that is, of the random component) are found in the summed interval, from which it follows that it is precisely this interval which is the most time-organized.

Shown in Fig. 10, B, is a histogram of the distribution of this summed interval, approximated to the normal distribution. From the figure it is evident that the experimental values of the parameters reveal deviations from the theoretical values. For the normal distribution under the given values of the mean and of σ we should expect a shallower peak and higher "shoulders" than exhibited by /55
the experimental data. On the basis of analogous proofs McGill reaches the conclusion that a regular rhythmic process takes place, and in conformity with his arguments it can be assumed that in our experiments as well the indicated interval is a reflection of a prescribed fixed interval τ, bounded by two control pulses.

Shown in Fig. 10, C, is a histogram of the distribution of intervals separating individual motions (the C interval), on the basis of experiments with an unspecified time of completion of the series of motions (4 test subjects, 630 cases). The dashes show the theoretical values, computed under the assumption that the distribution was normal. The differences between the computed and experimental values are the same as in Fig. 10, B.

Thus, it can be assumed that the execution of a series of learned actions by a human being is tied in with the presence of an internal rhythmic process which prescribes a uniform work rhythm. In our case the unit of this rhythm (a period) is the time expended in pressing a key plus the time expended in transferring the hand.

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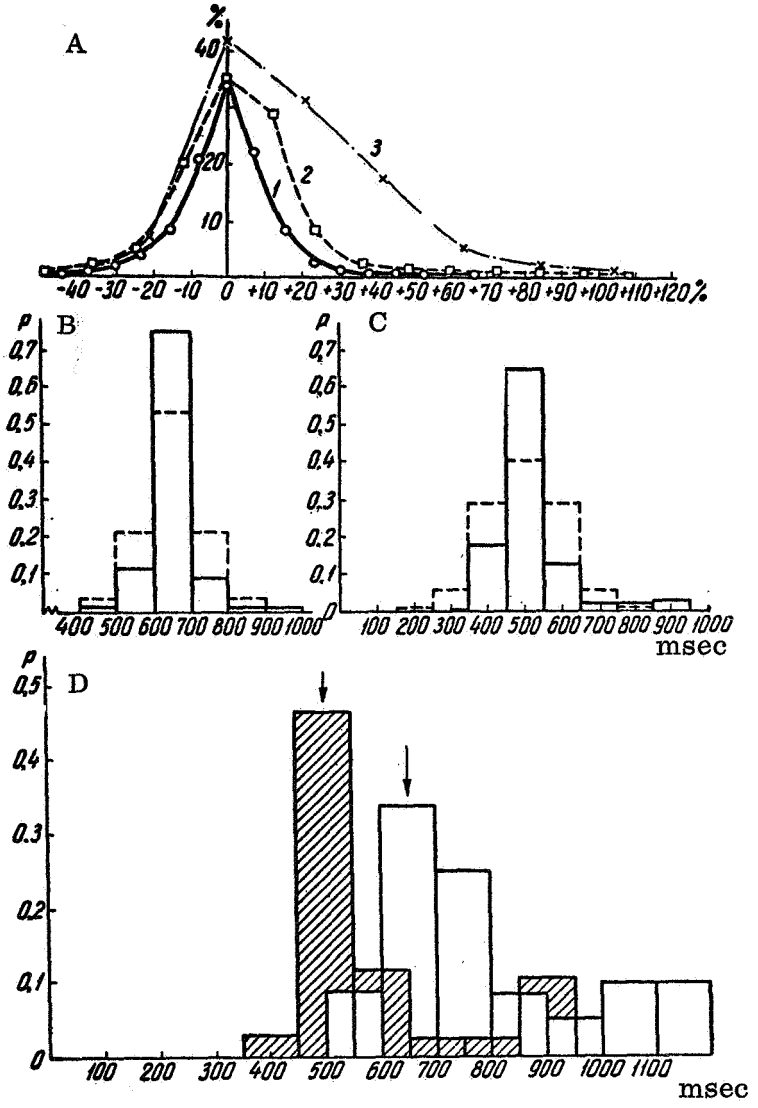

Figure 10. A-Curves of the Distribution of Deviations From the Value of the Arithmetic Mean for the Intervals.

1—Pressing + Hand-Transfer Times; 2—Hand-Transfer Time; 3—Pressing Time. B—Distribution of the Time Interval of One Motion (pressing + hand transfer) and Approximation to the Normal Distribution (dashes). C—Distribution of the "c" Interval and its Approximation to the Normal Distribution (dashes). D—Distribution of the "C" Interval for the Group of "Fast" and "Slow" Test Subjects. The Notation is the Same as in Fig. 8. The Arrows Indicate the Mean Values of the "c" Interval.

Now let us return to the problem of the structure of time organization of the inter-block pauses (the C interval). /55

Given in Fig. 10,D, are histograms of the distribution of the intervals separating blocks of actions for test subjects with different times of completion of the sequence ("fast" and "slow"). The number of cases was 440. The arrows indicate the mean values of the intervals characterizing the hand-transfer time in executing the actions within a block (the c interval) for each subgroup of test subjects. The figure shows that the peak of the distribution of the C interval coincides with the mean value of the c interval, but the slopes on the right are characteristic of the distribution of inter-block pauses.

In his model McGill considers such a case of functioning of a hypothetical rhythmic mechanism, when the frequency of the control pulses of the rhythm generator is greater than the response frequency. In this case some periods will be "empty," not accompanied by responses. The distribution of the intervals between responses for these cases will have a peak in the area of τ, according to McGill, but should be truncated on the right, while the mean length of the interval will exceed τ.

We believe that the distribution of the C interval is precisely such a case.

Based on the idea that the structure of control of a sequence of actions is hierarchical, it can be imagined that the issuance of instructions to execute a block of actions, which possibly takes place during the inter-block pauses, is somehow tied in with the operation of a higher level of the hierarchy than the issuance of commands to carry out actions within a block. It can be assumed that the operation of a higher hierarchical level is connected with the execution /56
of a large number of operations and requires more time. This circumstance leads to the premise that cases may arise when the next cycle of the rhythmic generator runs "idle," because the processes that ensure the realization of the response had not yet been completed at the instant the pulse was transmitted. In this case the next action is completed not within an interval close to τ, but within an interval close to 2τ, 3τ,... etc.

It should be noted that the "tail" of the distribution of the inter-block intervals has a rise approximately in the zone where the c interval is doubled (Fig. 10,D), which favors this assumption.

In previous communications, based on average values and on the assumption of a normal distribution, we presented data showing that the inter-block interval was greater than the other intervals separating individual actions. The analysis made in the present paper has shown that the mean values may not correctly reflect the differences between the inter- and intra-block pauses, since there is no normal distribution here. In conformity with McGill's model it is more correct to assume that in going from one sub-block (block) to the next a "skip" sometimes occurs in the operation of the rhythm generator, and because of this "skip" the histogram of the distribution of inter-block intervals reveals that the distribution slopes on the right, while the average value of the C interval proves to be higher than the value of the c interval. For this same reason, apparently, the quantity $1/\lambda\tau$ also proves to be high.

Conclusion

Returning to the problems posed at the beginning of the article on the processes which ensure the efficiency of human motor skills, we can now attempt to formulate a few answers.

Apparently, fast and accurate execution of a learned sequence of motor acts is based on the organization of the response activity, which is specific for a given sequence (a given motor task). This organization is connected with the formation, during the learning process, of a final control program whose elements are blocks or clusters of individual motor acts, interlinked. The individual motor acts are combined into linked blocks under certain conditions which create the prerequisites for detecting or formulating the structure describing the block of actions as a whole. We partially described these conditions at an earlier date [13]. Among them are the following: 1) the objects for motor acts which are consecutively arranged in the stereotype must be contiguously located /57
in space; 2) one and the same direction of hand displacement must be maintained in executing several motor acts; 3) it must be possible to describe a certain simple figure (a pattern, design, or symbol) by motion of the hand while executing several motor acts.

Obviously, the list of conditions we have presented is far from complete; further search and the establishment of new conditions uniting the individual actions into blocks are necessary. On the basis of what is already known, however, it can be assumed that the clustering process is a necessary participant in carrying out a learned sequence of actions.

It is possible that precisely this process is responsible for the high accuracy and speed of execution of a sequence of actions by a trained person, if it is assumed that the consecutive block of actions is completed not on the basis of successive instructions for each action, but of a general instruction to execute the entire group of responses.

Data on numerous transpositions of blocks of actions during the learning process induce us to believe that the nature of the links within blocks differs from that between blocks. The responses within blocks prove to be more closely knit. The time characteristics of stereotypes reveal the essential differences between processes which link motor acts within blocks and those which link blocks of acts to each other. The length of the pauses between individual actions within blocks is considerably smaller than the length of the pauses separating blocks and is characterized by fewer fluctuations. Special computations have shown that this difference cannot be explained by the distance the hand must travel in going from one key-pressing operation to the next.

One of the possible explanations for the difference in time of pause between consecutive actions when these actions make up a block or belong to different blocks is the recognition that there are two processes underlying the combination of actions. One governs the links between actions within a block and the other is associated with connections between the individual blocks of actions making up the stereotype. Further investigations will show what these processes are and how they differ from each other.

Apparently, the blocks of actions we studied can be associated with the presence of partial rules making up the final control program. It is not out of place to mention that there are apparently rules not only for blocking, but also for selection of actions. Analysis of some experiments we made in our laboratory may serve as an illustration of the possibility of such rules [14].

A large group of test subjects (35 people) developed stereotypes of motor acts consisting of successive key-pressing operations on a panel. /58 The test subjects were supposed to establish the order of actions by themselves, since the learning method consisted in a search and guess of each action, the test person being obliged to select one of eight possible keys. In so doing the test subject was permitted to search until he found the necessary response, and the correctness of the response was confirmed by the experimenter. An analysis was made of the errors committed by the test subjects during the learning process so as to determine the nature of his knowledge of the problem and of the order of priority of acquiring individual concrete items of knowledge. Let us consider two types of knowledge with respect to the described task.

The first type involves knowledge of concrete responses, i.e., their order in the stereotype. The external expression of this knowledge is a correct response (it is not preceded by a search). The second type involves knowledge with respect to certain abstract properties of the task. For example, in our problems there were no cases in which one and the same actions were repeated in succession (pressing one and the same key). The acquistion of such knowledge by the test subjects is expressed externally not only by the realization of the correct responses, but also by the nature of the errors. The errors will not contain a repetition in succession of one and the same key-pressing operation. In this connection we studied the nature of the errors made by the test subjects after a single familiarization (by searching and guessing) with a given stereotype.

It is natural to expect that people will commit many errors in doing such a problem. Of the 2,352 responses examined, 1,647 were erroneous. We were interested in how many errors are made in repeating the same action. If the test subjects do not know the overall characteristics of the problem, it is only natural to expect that when they decide which actions to take, they will not give preference to any one of the eight possible choices, and the number of errors connected with repetition of any action will be 1/8 of all the errors, or the expected numbers of errors from a total of 1,647 will be 206. Analysis of our experimental data showed that the second completion of the stereotype resulted in errors stemming from repetition in 28 cases, i.e., 1/59 of the total number of errors. This means that the test subjects set up or know a rule which limits the repetition of individual responses and divide the set of possible responses into repeating and alternating ones.

Thus, the formation of a final control program is based on a process connected with an evaluation of the sequence of actions to be completed, with the division of the entire set of responses into several subsets, and with the joining of individual responses into blocks having a certain structure by which they can be described as a whole.

The next question which must be examined is the rhythmic and uniform /59 manner in which a sequence of actions is executed.

The experiments and calculations we made showed that training of a human being to complete a series of simple homogeneous motions is tied in with rhythmic organization of the execution process. It was found that whether the time of completion of the series of actions was limited from the outsider or whether this time was unlimited, the total time of completion was reduced to a certain slightly fluctuating interval. It was found also that the total time of completion is uniform because the execution of individual parts (blocks) of the sequence of actions was uniform, while the latter is true because the execution of each individual action is uniform. Calculations of the distribution of the various intervals making up the time of completion of a sequence have demonstrated that the most regular interval, and the one closest to McGill's model, is the cycle of one motion (the key-pressing + hand transfer times). The absence of any appreciable difference in the data of the various series of experiments, with the time sometimes being prescribed externally, and sometimes not being prescribed at all, induces us to accept the notion that the rhythms we found are endogenous.

In connection with our data we must discuss several questions. In our previous communications we developed the idea that control of the order of the actions is hierarchical. We expressed the opinion that in executing a learned series of key-pressing actions, there are at least two higher levels of programming the order of the actions; in the upper level instructions are issued to perform a block of actions, followed by a stage in which the block "evolves" and the general instruction is converted into a series of commands to execute individual actions. It is natural to assume that the rhythmic mechanism, whose existence was discussed in the present article, functions at a level which cannot be located higher than the "evolution" level.

One more question must be considered — why is rhythmic organization of a series of actions expedient? Here we can put forth the following two speculative arguments: 1) the rhythms of motor activity we detected are governed by the "internal clocks" of man; 2) rhythmic organization of motion relieves the execution of individual natural motions of the sense of time indefiniteness, thus reducing the load on the mechanisms which evaluate information with respect to its own actions.

No data are available to us on the point where the mechanism which generates motor-activity rhythms is located, although it is natural to assume that it is found in the central nervous system. The problem of the search for such a mechanism is apparently one of the next problems of the physiology of the higher nervous activity.

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